

Limits on orbit crossing planetesimals in the resonant multiple planet system, KOI-730

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ABSTRACT

A fraction of multiple planet candidate systems discovered from transits by the Kepler mission contain pairs of planet candidates that are in orbital resonance or are spaced slightly too far apart to be in resonance. We focus here on the four planet system, KOI 730, that has planet periods satisfying the ratios 8:6:4:3. By numerically integrating four planets initially in this resonant configuration in proximity to an initially exterior cold planetesimal disk, we find that of the order of a Mars mass of planet-orbit-crossing planetesimals is sufficient to pull this system out of resonance. Approximately one Earth mass of planet-orbit-crossing planetesimals increases the interplanetary spacings sufficiently to resemble the multiple planet candidate Kepler systems that lie just outside of resonance. This suggests that the closely spaced multiple planet Kepler systems, host only low mass debris disks or their debris disks have been extremely stable. We find that the planetary inclinations increase as a function of the mass in planetesimals that have crossed the orbits of the planets. If systems are left at zero inclination and in resonant chains after depletion of the gas disk then we would expect a correlation between distance to resonance and mutual planetary inclinations. This may make it possible to differentiate between dynamical mechanisms that account for the fraction of multiple planet systems just outside of resonance.

1 INTRODUCTION

The latest tally of multiple planet candidate systems discovered by the Kepler mission (Batalha et al. 2012) includes 361 multiple-planet systems (Fabrycky et al. 2012). A statistical analysis, focused on the probability that binary stars are the most likely contaminant, finds that most of the multiple planet candidates are real planetary systems (Lissauer et al. 2012). The large number of recently discovered multiple planet systems represents a significant (by an order of magnitude) increase in the number of known multiple planet systems compared to those discovered from radial velocity surveys (Wright et al. 2011).

Both transit and radial velocity discovered multiple planet systems contain pairs of planets that are in first order mean motion resonance (Wright et al. 2009; Lissauer et al. 2011; Wright et al. 2011). In the Kepler transit systems, there are statistically significant excesses of candidate planet pairs both in resonance and spaced slightly too far apart to be in resonance (as delineated by Veras & Ford 2012), particularly near the 2:1 mean motion resonance (Lissauer et al. 2011; Fabrycky et al. 2012).

Planet migration due to tidal interaction with a gas disk is a possible mechanism through which convergent migration induces resonance capture, leaving planets in resonance (e.g. Lee & Peale 2002; Ferraz-Mello et al. 2003; Kley et al. 2004; Lee 2004; Papaloizou & Szuszkiewicz 2005; Thommes et al. 2008; Morbidelli et al. 2007;

Libert & Tsiganis 2011; Rein et al. 2012). Gravitational interactions between planets leading to planet-planet scattering events (e.g., Gózdziowski & Migaszewski 2009; Fabrycky & Murray-Clay 2010; Moore & Quillen 2012; Rein et al. 2012), turbulence in the disk (Pierens et al. 2011), and tidal interactions between planets (Papaloizou 2011; Lithwick & Wu 2012) have been proposed as mechanisms for pulling initially resonant planetary systems out of resonance. Interactions with planetesimals, for example as part of the ‘Nice’ model for the early solar system evolution, can also cause planets to diverge away from resonance (Tsiganis et al. 2005) (also see Thommes et al. 2008).

Simulations of planets and planetary embryos embedded in a gas disk allow planets to become trapped in resonance (Kley et al. 2004; Morbidelli et al. 2007; Rein et al. 2012). After the gas disk dissipates, newly formed planets may be left in a chain of mean-motion resonances (Morbidelli et al. 2007; Matsumura et al. 2010; Moeckel & Armitage 2012). By a chain of mean motion resonances, we mean that each consecutive pair of planets is in a $j + 1 : j$, first order, mean motion resonance (though the integer j can differ for each pair). Resonant chains have been chosen as initial conditions for studies of planetary system evolution after the depletion of the gas disk (e.g., Tsiganis et al. 2005; Thommes et al. 2008; Batygin & Brown 2010). When pairs of planets are in or

near mean motion resonances, there may be a librating or nearly fixed Laplace angle involving three or more bodies. Three-body resonances (e.g., those comprised of zero-th order terms; Quillen 2011) may be present even when pairs of planets are not in first order mean motion resonances. A system in a resonant chain of first order resonances does not necessarily exhibit a librating Laplace angle involving three or more bodies.

The four planet candidate system, KOI-730, contains planets with periods that satisfy the ratios 8:6:4:3 to approximately 1 part in 1000 or better (Lissauer et al. 2011). These ratios imply that the outer two and inner two planet pairs are in (or near) a 4:3 mean motion resonance and that the middle pair of planets is in (or near) a 3:2 resonance. In this study we explore the evolution of a similar model four planet system in proximity to a planetesimal disk. We ask: how much mass in orbit-crossing planetesimals is sufficient to pull this system out of resonance?

For a pair of planets and a first order mean motion resonance, Fabrycky et al. (2012) define a parameter, $\zeta_{1,1}$, that measures proximity to a first order mean motion resonance,

$$\zeta_{1,1} \equiv 2 \left(\frac{1}{\mathcal{P} - 1} - \text{Round} \left(\frac{1}{\mathcal{P} - 1} \right) \right), \quad (1)$$

where $\mathcal{P} = P_i/P_j$ (greater than 1) is the observed period ratio of planets i, j (and as defined in the appendix by Fabrycky et al. 2012). The ‘Round’ function rounds to the nearest integer. The parameter $\zeta_{1,1} = 0$ at a $j + 1 : j$ first order resonance and the function goes from -1 to 1 at second order resonances ($j + 2 : j$). The parameter used by Lissauer et al. (2011), $\zeta_1 = 1.5\zeta_{1,1}$ and varies from -1.5 to 1.5.

The probability density distribution of ζ_1 values generated from all pairs of Kepler planet transit candidates, for pairs residing in a single system, exhibits a peak at about $\zeta_1 \approx -0.2$, (see Figure 11 by Lissauer et al. 2011 and Figure 5 by Fabrycky et al. 2012). For KOI-730, $\zeta_1 = -0.0123, -0.0186, -0.0063$ for the inner pair, middle pair and outer pair of planets, respectively (Fabrycky et al. 2012), consequently the system is likely to be in or very near a resonant chain. By integrating a system modeled after the KOI-730 system that is initially in a chain of resonances, we ask: how much mass in orbit-crossing planetesimals would increase the interplanetary spacing so that $\zeta_1 \sim -0.2$? We also note that due to relatively low mass of the planets and their proximity to the star, their resonant widths are likely smaller than $\zeta_1 = 0.1$, as first order mean motion resonance width scales approximately with mass to the 2/3 power (e.g. Wisdom (1980)).

We first describe how we find resonant chain configurations for the KOI-730 system. We use these configurations to construct initial conditions for N-body integrations that include a planetesimal disk. A summary and discussion follows.

2 SETTING UP RESONANT CHAIN CONFIGURATIONS

We first describe how we find orbital elements consistent with a 8:6:4:3 ratio resonant chain for a four planet system similar to the KOI-730 multiple planet system. We find res-

Table 1. Masses and Periods for the planet candidates in the KOI 730 system and initial orbital elements

Mass (M_\oplus)	Period (days)	a	e	ω	M
2.5	7.3840	1.0	0.055589	-2.808830	1.216544
3.7	9.8487	1.211221	0.071128	-0.739956	2.841707
8.6	14.7884	1.586171	0.050110	1.453201	-0.924252
6.2	19.7213	1.920630	0.043428	-1.990222	-0.172501

Planet masses for the KOI 730 system are computed from radii based on transit durations taken from http://archive.stsci.edu/kepler/planet_candidates.html (Batalha et al. 2012), using equation 3. The observed periods are given in days and are taken from the same website. The rightmost four columns give the orbital elements we used as initial conditions (see section 2). Here ω is the argument of pericenter and M the mean anomaly. Initial inclinations and the longitudes of the ascending node were set to zero. These orbital elements were taken from the integration shown in Figure 1.

Table 2. N-body Simulations

Simulation	Planetesimal Mass (M_\oplus)	Orbit-crossing mass (M_\oplus)
Z	0	0
M	10^{-4}	0.04
E3	3.3×10^{-4}	0.12
E	10^{-3}	0.46
N5	3.3×10^{-3}	1.7
N	1.67×10^{-2}	16.6

Each simulated disk contains 1024 equal mass planetesimals. The planetesimal masses in units of Earth mass are listed in the second column. The third column shows the total mass in planetesimals (in Earth masses) that crossed the orbits of any of the planets at the end of the simulation. The names of the simulations are related to the masses of the planetesimal disks. The Z simulation has a zero mass disk. The M, E and N simulations have disks with Mars, Earth and Neptune masses, respectively. The E3 and N5 simulations have disks with a third Earth and a fifth Neptune mass, respectively.

onant chain configurations by integrating a 5 body system under the influence of gravity (four planets and the central star) and including a Stokes drag-like form for dissipation that induces both migration and eccentricity damping (as previously done by Beaugé et al. 2006; Batygin & Brown 2010; Libert & Tsiganis 2011). The drag gives a force per unit mass in the form adopted by Beaugé et al. (2006)

$$\mathbf{F}_{drag} = -\frac{\mathbf{v}}{2\tau_a} - \frac{\mathbf{v} - \mathbf{v}_c}{\tau_e} \quad (2)$$

where \mathbf{v} is the planet velocity and \mathbf{v}_c is the velocity of a planet in a circular orbit at the current radius (from the star) of the planet. We use a 4th order adaptive step-size Hermite integrator (that described by Makino & Aarseth 1992) with the addition of the above drag force. We work in units of the innermost planet’s initial orbital period or 7.3840 days.

The drag force induces radial migration on a timescale $\frac{a}{\dot{a}} \sim \tau_a$, and eccentricity damping on a timescale $\frac{e}{\dot{e}} \sim \tau_e$ where a, e are the planet’s semi-major axis and eccentricity, respectively. Resonant capture can only occur when the drift rate, \dot{a} , is sufficiently slow such that the square of libration frequency in resonance exceeds the drift rate (this

defines the adiabatic limit; Quillen 2006). Following resonant capture, eccentricities of planets can increase as they drift inwards, (Lee & Peale 2002), causing instability (e.g., Kley et al. 2004; Libert & Tsiganis 2011; Rein et al. 2012). For two planet systems, an equilibrium state may be reached that depends on the ratio $K \equiv \frac{\tau_a}{\tau_e}$ (Lee & Peale 2002). As discussed by Rein et al. (2012), if two bodies lie initially outside the 2:1 or 3:2 resonance, then they are more likely to capture in one of those than in the 4:3 resonance. Here we require that the outer and inner pair of planets are captured into the 4:3 resonance, consequently we began the integration with planets spacings just outside the desired resonances. The migration rates were adjusted so that the migration is sufficiently fast that capture into weaker second order resonances such as the 5:3 or the 7:5 is unlikely.

The masses of the four planets were set from the radii measured from the transit durations and reported by Batalha et al. (2012). We adopt the power-law relationship for planetary mass, M_p , as a function of radius, R_p , used by Lissauer et al. (2011); Fabrycky et al. (2012),

$$M_p = M_{\oplus} (R_p/R_{\oplus})^{\alpha}, \quad (3)$$

where M_{\oplus}, R_{\oplus} are the mass and radius of the Earth, and the exponent $\alpha = 2.06$ for $R_p > R_{\oplus}$. This choice is motivated by Solar System planets as it is a good fit to Earth, Uranus, Neptune, and Saturn. KOI-730's surface gravity and effective temperature (reported in Table 9 by Batalha et al. 2012, with surface gravity $\log_{10} g(\text{in cgs}) = 4.39$ and effective temperature $T_{\text{eff}} = 5599$ K) are similar to that of the Sun (with $\log_{10} = 4.43$ and $T_{\text{eff}} = 5780$ K) so we computed planet to stellar mass ratios from the estimated planet radii, equation 3 and using a Solar mass for the host star. Estimated planet masses and their periods are summarized in Table 1. The estimated planet masses for the KOI-730 system are much lower than the approximately Jupiter mass planets considered by Rein et al. (2012) for the HD2006964 system. The 4:3 resonance may be more stable in lower mass systems.

An integration is shown in Figure 1 with a) showing the four semi-major axes as a function of time and b) showing the period ratios of consecutive pairs of planets. Semi-major axes are shown in units of the initial innermost planet's semi-major axis. The timescales τ_a and τ_e can be chosen separately for each planet. We set τ_a for the innermost planet to be extremely long (10^9 orbits), and that for the outer 3 planets to be progressively shorter ranging from 10^6 to 10^5 orbits. Note that 10^5 orbits of the innermost planet is only approximately 2000 years. We arranged the drift rates so that the outer planet migrates more quickly than the inner ones. After the outer planet captures the third planet, the two together migrate more slowly than the outer planet. To maintain a constant drift rate for the pair, the third planet was set with a longer value for τ_a , and similarly, τ_a for the second planet was chosen to be larger than that for the third planet.

Once in resonance, the eccentricities of the planets increase as the planets drift inwards. A steady state can be reached with eccentricity values that depend on the size of the eccentricity damping, set here with τ_e (Lee 2004). High values of τ_e (corresponding to low levels of damping) are associated with high planet eccentricities, whereas low values of τ_e reduce the eccentricities of the planets. We found

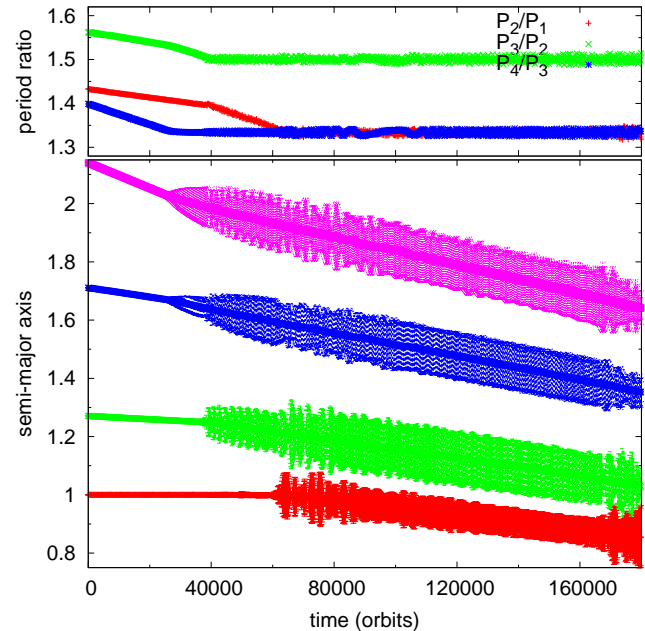


Figure 1. a) Semi-major axes of the four planets under the influence of a forced dissipative process as a function of time. b) Period ratios for the same integration. This integration was used to generate initial orbital elements for the four planets in the simulations including planetesimals. We took orbital elements from the time at 70,000 orbits.

that this system became unstable without significant eccentricity damping. Consequently we set the level of eccentricity damping sufficiently high, $\tau_e \sim 10^4$, so that the system remained in resonance after all planets were captured into resonance. This value is high compared to that predicted for tidal interactions between disk and planet. Large K values (up to 100) have been used previously (Batygin & Brown 2010) to generate stable initial resonant conditions for subsequent integration, as we do here. As can be seen from Figure 1 the outer pair of planets first captures into resonance, then the middle pair and lastly the innermost pair is captured into resonance. Morbidelli et al. (2007) stressed that the order of captures can affect the resonant angles. The 8:6:4:3 ratios imply that the second and fourth planets are near or in a 2:1 mean motion resonance and the first and third planets are also near such a resonance. We find that fine-tuning in initial planet semi-major axes, forced drift and eccentricity damping rates are required to put the system in the 8:6:4:3 chain of resonances.

We are not investigating formation mechanisms (see Rein et al. 2012 for a first investigation into this tricky problem).

3 N-BODY SIMULATIONS WITH A PLANETESIMAL DISK

Using orbital elements from the converging integration discussed above, we run N-body simulations of the four planets, initially in resonance, in the vicinity of a planetesimal disk and about a central star. These simulations were run with

the software QYMSYM (Moore & Quillen 2011). QYMSYM is a GPU-accelerated hybrid second order symplectic N-body integrator which permits close encounters similar to the *MERCURY* software package developed by Chambers (1999).

We began each simulation with four planets in a resonant chain and an external planetesimal disk comprised of 1024 equal mass planetesimal particles. Orbital elements for the four planets in the integration shown in Figure 1 at time $t = 70,000$ orbits, and listed in Table 1, were used as initial conditions for these integrations.

The planetesimal disk particles ranged in semi-major axis from $a_{min} = 1.95$, just outside the outermost planet, to $a_{max} = 2.95$. The distribution of planetesimal semi-major axes is flat with probability independent of semi-major axis within a_{min} and a_{max} . The initial eccentricity and inclination distributions were chosen using Rayleigh distributions with the mean eccentricity e equivalent to twice the mean value of the inclination i and $i = 0.01$. The initial orbital angles (mean anomalies, longitudes of pericenter and longitudes of the ascending node) for the planetesimals were randomly chosen. We work in units of the initial orbital period of the innermost planet.

Six simulations were run, each with different planetesimal mass. We included a test case with massless disk particles to check the stability of the integration lacking planetesimals. We labeled the simulations by the mass of the planetesimal disk, with simulation Z corresponding to a massless planetesimal disk while simulations M, E, and N correspond to Mars, Earth and Neptune mass disks. Simulation E3 and N5 refer to simulations with a third of an Earth mass and a fifth of a Neptune mass disk, respectively. Each simulation was run for 500,000 orbital periods (or 10^4 years as the innermost planet's orbital period is only 7.4 days).

The timestep was chosen to be 0.08607 out of a possible 2π orbit. Given this step size, energy conservation (measured by dE/E) was 10^{-3} or better for all simulations except during the simulation labeled N (its energy conservation was 8×10^{-3}).

Due to the proximity of the planets of KOI-730 to their star, the planets practically fill their Hill sphere. The large fraction of the Hill sphere filled limits the escape velocities of close encounters. Our integrator does not check for collisions though it does integrate close encounters. To take into account the large fraction of the Hill sphere filled, we adjusted the smoothing lengths during close encounters between planets and planetesimals.

In these simulations we used a smoothing length of $s = 1 \times 10^{-3}$, which corresponds to a distance that is slightly larger than the radii of the innermost planet (about $1.1\times$). The Hill radius of the innermost planet, which would be the smallest of the four due to it both being the closest to the central star as well as the least massive, is a little more than ten times larger (about $13.5\times$) than this smoothing length.

We have checked that the inclination distributions and extent of migration are not strongly dependent on the assumed smoothing length. This was done by comparing the results of our simulation described above that have planet radii sized smoothing lengths to a separate set of identical simulations only with a smoothing length 100 times smaller.

During each simulation we computed the mass in planetesimals that crossed the orbits of the planets. We count

a planetesimal as orbit-crossing if its pericenter is less than the apocenter of the outermost planet. The total planetesimal mass that crossed the orbits of the planets at the end of the simulations are also listed in Table 2. As we will discuss below, these masses can be used to place limits on the total quantity of planetesimals that may have crossed the orbits of planets in the KOI-730 system.

3.1 Planetary migration in the N-body simulations

Figure 2a) shows period ratios for each consecutive pair of planets as a function of time for all 6 N-body simulations. For the inner and outer planet pairs (initially in 4:3 resonance) the period ratio is shown subtracted by $4/3$. The middle planet pair (initially in 3:2 resonance) is plotted subtracted by $3/2$. Our test case Z simulation (bottom panel in Figure 2a) remains stable throughout the integration, consequently we are confident that the orbital elements chosen from our capture integration are stable. It is possible that this system becomes unstable on a timescale longer than 500,000 orbits.

The M, E3, E, N5, and N simulations contain disks with increasing mass. Because of the proximity of the outermost planet to the inner edge of the planetesimal disk, the outer planet migrates outwards as planetesimals cross the orbits of the planets and exchange angular momentum with them. The outer planet migrates furthest in the simulations with highest disk mass. For the most part, period ratios increase, though as the planets separate, mean motion resonances, as they are crossed, can cause jumps in both eccentricity and semi-major axis. At some times we see a signature of three-body resonances, when the period ratio for one consecutive pair (of three planets) increases as the period ratio of the other consecutive pair decreases (Quillen 2011).

The Z simulation remains locked in resonance throughout the integration. However, we see that the M and E3 simulations no longer maintain their chains of MMR's at 250k and 175k orbits respectively. The E simulation is removed from resonance at approximately 50k orbits. This allows us to estimate the mass in planet-crossing planetesimals required to pull this system out of resonance for each simulation, finding on average $m_c \sim M_{Mars}$. The N and N5 simulations have their planets out of resonance very quickly due to the larger amount of orbit crossing mass early in the simulation. In both of those simulations the planets are out of resonance too quickly for us to accurately determine how much mass was orbit crossing. Simulations E, E3, and M all have total crossing masses within an order of magnitude of each other.

For each integration we compute $\zeta_{1,1}$ (equation 1) as a function of time for each consecutive pair of planets. Figure 2b shows the $\zeta_{1,1}$ function computed from all consecutive planet pairs for the same simulations. Variations in the $\zeta_{1,1}$ parameter are largest for the most massive disk. We see from Figure 2b that $\zeta_{1,1}$ approaches -0.2 at a time of about 50k orbits for planets 3 and 4. This allows us to estimate the amount of planetesimal disk mass that would move a system sufficiently out of resonance to contribute to the peak seen in the ζ_1 distribution of the Kepler multiple planet candidates. Based on the mass in orbit-crossing planetesimals in simulation N5 we estimate $m_c \approx M_{\oplus}$ is required to pull

a system initially in a resonant chain sufficiently far apart to give a ζ_1 equivalent to the position of the peak seen in the ζ_1 distribution by Fabrycky et al. (2012) (see their Figure 5).

We note in Figure 2b that we find that the $\zeta_{1,1}$ function does not always decrease for each planet pair. Furthermore, during migration we see a range of $\zeta_{1,1}$ values. To produce a peak in the distribution of ζ_1 we would require a very specific or fine tuned value for the mass in orbit-crossing planetesimals for multiple planet systems that are originally in resonant chains.

Figure 2c shows the inclinations of all planets as a function of time. We see that the planet inclinations increase to a couple of degrees in the simulations with the most massive disks. We have checked that simulated planetesimals have not been ejected at high velocity. The masses of our simulated planetesimals is quite low (see Table 1) and the inclinations slowly increase. The increases in planet inclination are unlikely to be numerically generated during encounters and due to extreme scattering events. The smooth increase in inclinations can be attributed to a combination of gravitational heating caused by scattering of planetesimals and to crossing of vertical resonances resulting from the migration of the planets (as seen by Libert & Tsiganis 2011).

Figure 2a implies that planet inclinations in closely spaced multiple planet systems depend on the total planetesimal mass that has crossed the orbits of the planets.

Fabrycky et al. (2012) find that mutual inclinations for the multiple planet systems lie in the range $1.0 - 2.3^\circ$ and that their distribution is well modeled by a Rayleigh distribution with standard deviation $\sqrt{\langle i^2 \rangle} = 1.8^\circ$. We see in Figure 2c that the inclinations rise above this value when the total mass in orbit crossing planetesimals exceeds $17M_\oplus$, or about one Neptune mass. Therefore, closely packed systems similar to the KOI-730 system likely have not experienced an era similar to the Late-Heavy Bombardment in our Solar system. From this comparison we tentatively place a limit on the total mass in orbit crossing planetesimals during the lifetime of the KOI-730 system of $m_c \lesssim M_\oplus$.

4 DISCUSSION AND CONCLUSION

Using an N-body integrator with the addition of drag causing convergent migration and eccentricity damping, we constructed a resonant chain for four planets with period ratios 8:6:4:3, and used planet masses estimated for the KOI-730 multiple planet system. Orbital elements from this integration were then used as initial conditions for N-body simulations with the four planets which included an external planetesimal disk. Interactions with the planetesimal disk allowed the planets to migrate, primarily diverging rather than converging, as expected.

We find that one Earth mass of orbit-crossing planetesimals is sufficient to pull a system similar to the KOI-730 system out of its chain of mean motion resonances. As planet radii estimated from transit data depend on stellar radii, it is possible that we have over or underestimated the masses of the planets in the KOI-730 system. The distance migrated by a planet should scale with the mass in planetesimals that it interacts with. However, mean motion resonant widths are larger when planet masses are larger. We find that it is more

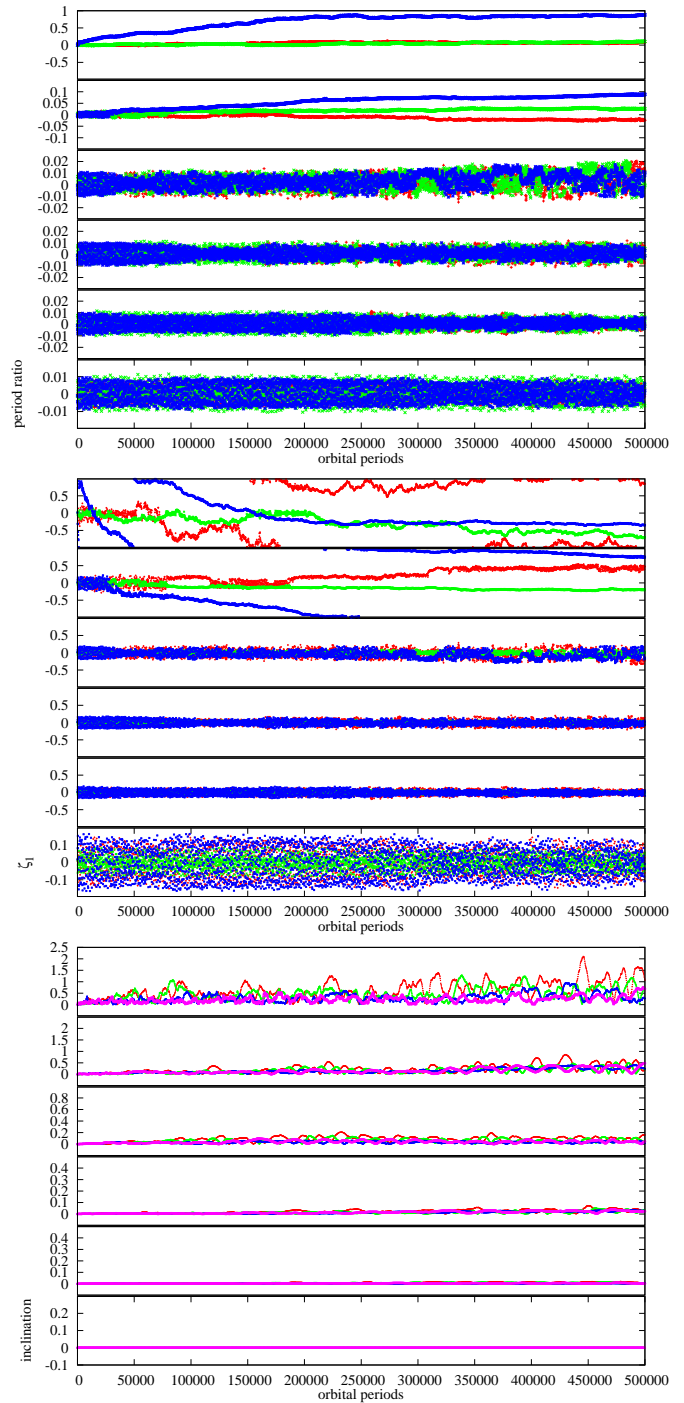


Figure 2. a) Period ratios for consecutive pairs of planets subtracted by their initial value and as a function of time. Each panel shows period ratios for a different simulation. From top to bottom, the planetesimal disk mass decreases. Red, green and blue lines refer to the inner, middle and outer consecutive planet pairs, respectively. b) $\zeta_{1,1}$ parameters computed from consecutive planet period ratios and for the same simulations. The colors are the same pairs as in a). c) Planet inclinations in degrees as a function of time for the same simulations. The red, green, blue and pink lines refer to the first (inner), second, third and fourth (outer) planets, respectively.

difficult to form a resonant chain via resonant capture and such chains are less stable when the planets are more massive. Consequently, the amount of material required to pull a system out of resonance may not scale linearly with planet mass. Nevertheless, we expect that if the true planet masses are larger than adopted here, a larger mass in orbit-crossing planetesimals would be required to pull this system out of resonance and vice-versa if the planets are less massive.

After the system is out of resonance, we find that it remains stable. Our simulations do not exhibit planet/planet orbit crossing events. The KOI-730 system, comprised of sub-Neptunian mass planets, can be compared to the HR8799 system, comprised of hyper-Jovian mass planets in resonance. When the HR8799 system is pulled out of resonance, the system is extremely unstable (Gózdziwski & Migaszewski 2009; Moore & Quillen 2012).

The KOI-730 system is likely in (or very close to) a resonant chain. Because interactions with planetesimals and tidal interactions between planets primarily cause planetary orbits to slowly diverge (Papaloizou 2011; Lithwick & Wu 2012) and so pull systems out of resonance, we can be fairly confident that processes following depletion of a gas disk did not put this system in resonance. Because the system is currently near or in resonance, only a small mass in planetesimals could have ever crossed the orbits of these planets. We infer that this system either lacks a debris disk or contains one that is so diffuse or stable that less than an Earth mass of debris has ever crossed the orbits of these planets.

We also find that an Earth mass of orbit-crossing planetesimals can cause the planets to migrate far enough that the system lies sufficiently outside of resonance to resemble the Kepler systems with $\zeta_1 \sim -0.2$ where the peak of the distribution lies (Fabrycky et al. 2012; Lissauer et al. 2011). However we expect that different planetary systems would have different quantities of orbit-crossing planetesimals. Consequently we would not expect that a narrow peak in the ζ distribution would arise in a distribution of planetary systems. Fine tuning in the quantity of planetesimals may be required to account for the peak seen in the ζ distribution. The tidal damping scenario for pulling pairs of planets away from resonance (Lithwick & Wu 2012; Papaloizou 2011) may more naturally account for a peak in ζ .

We find that the more an initially flat planetary system interacts with planetesimals, the higher the mean planet inclinations. If somewhere between a few earth masses to about a Neptune mass of planetesimals cross the orbits of the planets, the planet inclinations can increase to a few degrees. This is sufficiently high that they would not be all simultaneously be detected in transit. The tidal circularization scenario would not give a relation between migration distance and inclination. However over short distances, as planets migrate and they cross vertical resonances, we would expect a correlation between migration distance (and so distance out of resonance) and inclination. Study of the relation between the inclination and period distributions of the Kepler systems may differentiate between roles of tidal forces and planetesimals.

It is possible that the transiting multiple planet systems discovered by the Kepler mission are more compact or lower mass than radial velocity discovered planetary systems. Can we differentiate between the tidal interaction mechanism for pulling systems out of resonance and that

caused by interactions with planetesimals? If planetesimals interact with planets, then it is likely that planet inclinations can increase as planets cross vertical resonances. It may be possible to differentiate between these two mechanisms based on inclination distributions as tidal interactions likely do not increase inclinations but planet/planetesimal interactions can. Note that Libert & Tsiganis (2011) have shown that resonant capture for higher planet mass systems can also induce inclination variations. However, additional mechanisms, such as turbulence associated with a gas disk or secular perturbations from distant planets could also affect the inclination distributions. Future studies can probe the role of planetesimals, and migration associated with scattering them, in accounting for the inclination distributions of the Kepler planetary systems.

We have focused here on interactions with a low eccentricity planetesimal disk. When it encounters a planet, a high eccentricity planetesimal is less strongly gravitationally focused than a low eccentricity one. Consequently, high eccentricity objects are less effective at scattering a planet or inducing migration. Our limit on the total mass in orbital crossing planetesimals can be considered a lower limit as we began with a low eccentricity disk. Future studies can explore the possibility that compact Kepler systems harbor massive outer planetary systems and high eccentricity cometary populations.

In summary, we believe that closely spaced, low inclination multiple planet Kepler systems likely have either low mass or extremely stable debris disks. There appears to be a relation between the inclination and amount of migration for a planet. The inclination distributions may make it possible to differentiate between dynamical scenarios for pulling planets out of resonance. Due to the improbability of a Late Heavy Bombardment like scenario for KOI-730, we believe these inclinations are probably caused by crossing vertical resonances.

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